

What triggers black-hole growth? Insights from star formation rates

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ABSTRACT

We present a new semi-analytic model for the common growth of black holes (BHs) and galaxies within a hierarchical Universe. The model is tuned to match the mass function of BHs at $z = 0$ and the luminosity functions of active galactic nuclei (AGNs) at $z < 4$. We use a new observational constraint, which relates the luminosity of AGNs to the star-formation rate (SFR) of their host galaxies. We show that this new constraint is important in various aspects: a) it indicates that BH accretion events are episodic; b) it favours a scenario in which BH accretion is triggered by merger events of all mass ratios; c) it constrains the duration of both merger-induced star-bursts and BH accretion events. The model reproduces the observations once we assume that only 4 per cent of the merger events trigger BH accretion; BHs accretion is not related to secular evolution; and only a few per cent of the mass made in bursts goes into the BH. We find that AGNs with low or intermediate luminosity are mostly being triggered by minor merger events, in broad agreement with observations. Our model matches various observed properties of galaxies, such as the stellar mass function at $z < 4$ and the clustering of galaxies at redshift zero. This allows us to use galaxies as a reliable backbone for BH growth, with reasonable estimates for the frequency of merger events. Other modes of BH accretion, such as disk-instability events, were not considered here, and should be further examined in the future.

Key words:

1 INTRODUCTION

Most massive galaxies in the local Universe host supermassive black holes (BHs) in their centres (Kormendy & Richstone 1995). Active periods of accretion onto such objects, seen as active galactic nuclei (AGNs), are observed in less than a few percent of the objects. Consequently, models of BH evolution rely on assumptions about the triggering of accretion events and the connection, if any, with the host galaxy evolution. A key problem in such studies relates to the big difference in scale between the cold gas in the galaxy (distributed over several kpc) and the inner disk around the BH (typically smaller than a parsec). Various suggestions have been made to bridge the gap between these scales, including: merger triggered accretion, secular processes in the host galaxy including disk instabilities¹, mass loss from evolved stars, star formation (SF) activity in the central region, and more.

The merger scenario is motivated by two different lines of ev-

idence. First, N -body and hydrodynamical simulations of merging galaxies suggest that such events drive a large amount of cold gas into the centre of the merging system, resulting in the formation of a large bulge or a spheroidal galaxy (Barnes & Hernquist 1991; Mihos & Hernquist 1996; Cox et al. 2006; Robertson et al. 2006; Di Matteo et al. 2007). Second, AGN activity is observed in local ultra-luminous infrared galaxies (ULIRGs), which are known to be associated with energetic merger events (Sanders et al. 1988; Sanders & Mirabel 1996; Surace et al. 2000; Canalizo & Stockton 2001; Veilleux et al. 2009). Observationally, an evidence for a direct connection between minor mergers and AGN activity is more difficult to establish.

Recent studies show that most galaxies at $z < 2$ that host a low-luminosity AGN do not show morphological evidence for major merger events in their recent history (Gabor et al. 2009; Cisternas et al. 2011; Kocevski et al. 2012; Schawinski et al. 2012). Only high-luminosity AGNs are related to major mergers (Treister et al. 2012). This has been taken to indicate that the role of secular processes in driving gas to the centre of galaxies and feeding the BH is important and very common at almost all redshifts (Efsthathiou et al. 1982; Genzel et al. 2006; Elmegreen & Burkert 2010; Ceverino et al. 2010; Bournaud et al. 2012). The nature and frequency of such internal events are not fully understood, partly

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¹ In this work we use the terms “secular evolution” and “secular processes” to indicate all types of internal processes within a galaxy. These include events of disk instability that might induce bursts of star-formation. Secular evolution does not include events related or triggered by galaxy mergers.

because it is difficult to discriminate them from minor mergers. Nonetheless, various structural properties of galaxies have been suggested to distinguish between secular and merger events (Kormendy et al. 2009).

Most of the studies mentioned above have measured the mass ratio in mergers by visual inspection, involving a large uncertainty. Moreover, there may well be a time-delay between the merger event and the peak luminosity of the AGN. Since recently merged galaxies have similar clustering properties as other galaxies of the same mass (Bonoli et al. 2010), the effect of time-delay is difficult to detect (however, it might be constrained by detailed analysis of galaxy spectra Davies et al. 2007; Wild et al. 2007; Wild et al. 2010).

Other internal mechanisms within a galaxy were proposed as a trigger for BH accretion. Hopkins & Hernquist (2006) have demonstrated that feedback from the BH can regulate low levels of BH accretion. Best et al. (2005) have argued that observations of radio-loud AGNs provide indications for hot gas accretion into BHs.

The mass of super-massive BHs in galactic centres is strongly correlated with both the bulge mass (Magorrian et al. 1998; McLure & Dunlop 2002; Marconi & Hunt 2003; Häring & Rix 2004; Sani et al. 2011; McConnell & Ma 2012) and the bulge velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000). These relatively tight correlations suggest that the mechanisms which are responsible for building up the mass in bulges are also related to BH growth and hence the triggering of AGN activity. However, since the mass is an integrated quantity, these correlations could also originate from the hierarchical aggregation of mass (Hirschmann et al. 2010; Jahnke & Macciò 2011). Better understanding of the various accretion scenarios is therefore required in order to understand the BH-bulge relationships.

Further hints for the nature of BH accretion could be provided by relating AGN luminosities to SF rates (SFRs) of their host galaxies. Unlike morphological studies, SFRs are well defined, and can be quantitatively compared between various populations of galaxies. Studies of SFRs and AGNs luminosities in large spectroscopic surveys, like the Sloan Digital Sky Survey (SDSS, York et al. 2000) suggest that many AGNs are located within star-forming galaxies (Kauffmann et al. 2003; Wild et al. 2007; Salim et al. 2007; Daddi et al. 2007; Davies et al. 2007; Silverman et al. 2009; Netzer 2009; Wild et al. 2010; Mor et al. 2012; Rovilos et al. 2012; Tommasin et al. 2012). Here we choose to highlight the recent measurements by Shao et al. (2010) and Rosario et al. (2012) that are based on SFRs obtained by *Herschel* in the FIR, and are more reliable than UV-based SFRs. According to Rosario et al. (2012), such SFRs are uncorrelated with the AGN luminosity at low and intermediate luminosities and at high redshift. However, *high* luminosity AGNs at low and intermediate redshifts do show a correlation with the SFRs of their host galaxies.

In this paper we use a semi-analytic model (SAM) of galaxy-formation combined with BH evolution, in order to examine the correlations between SFRs and AGN luminosities. SAMs are naturally being used for this problem as they provide a statistical sample of galaxies that is in general agreement with observations (Kauffmann & Haehnelt 2000; Croton et al. 2006; Bower et al. 2006; Malbon et al. 2007; Monaco et al. 2007; Somerville et al. 2008; Bonoli et al. 2009; Fanidakis et al. 2011; Fanidakis et al. 2012; Hirschmann et al. 2012).

Our study is different from previous SAMs in various aspects. First, we use the SAM from Neistein & Weinmann (2010) and Wang et al. (2012) that fits the stellar mass function of galaxies at $0 < z < 4$ and the clustering of galaxies at low redshift. As a result, the star-formation histories and merger-rates of galaxies within

the model are in broad agreement with the observed Universe. Second, we do not attempt to model AGN feedback as a function of each specific AGN but rather assume that the galaxies within our model experience an average AGN feedback that depends only on halo mass. Third, we aim to match a wide range of AGN observations, including the relation between SFR and AGN luminosity mentioned above, and the fraction of host galaxies that are experiencing major merger events.

Various recent empirical models of BHs and AGNs evolution are aimed to fit the BH mass function and AGN luminosity functions (e.g. Wyithe & Loeb 2003; Lapi et al. 2006; Hopkins et al. 2006, 2007, 2008; Shankar et al. 2009; Shankar 2010; Shankar et al. 2012; Conroy & White 2012; Draper & Ballantyne 2012). Here we choose to use SAMs, as they allow a more direct modelling of SFRs and merger fractions of individual objects, in close contact with the formation history of their host haloes. These features play a key role in our model.

This paper is organized as follows. In section 2 we describe the model ingredients and the details of computing all the properties of galaxies and BHs. Section 3 includes a detailed comparison between the model and observations. The results are summarized and discussed in section 4. This study is based on the cosmological parameters that are used by the Millennium simulation: $(\Omega_m, \Omega_\Lambda, \sigma_8, h) = (0.25, 0.75, 0.9, 0.73)$. Throughout the paper we use \log to denote \log_{10} .

2 THE MODEL

2.1 Galaxy formation and evolution

The SAM used in this work is adopted from Wang et al. (2012), and is based on the formalism of Neistein & Weinmann (2010). The model follows galaxies inside the complex structure of subhalo merger-trees taken from a large N -body cosmological simulation (the Millennium simulation, Springel et al. 2005). This simulation follows 2160³ dark-matter particles inside a periodic box of length $500 h^{-1} \text{Mpc}$, with a minimum halo mass of $1.72 \times 10^{10} h^{-1} \text{M}_\odot$.

Our SAM includes the effects of cooling, star formation (SF), accretion, merging, and feedback. Unlike other SAMs, these laws are simplified to be functions of only the host subhalo mass and redshift. We have shown in Neistein et al. (2012) that this concept is sufficient for the SAM to reproduce the gas and stellar mass content of galaxies, on an object by object basis, as obtained from a hydrodynamical simulation to an accuracy of 0.1 dex. Consequently, this SAM is complex enough to accurately follow the SF histories of galaxies.

The specific model used here was presented in Wang et al. (2012) as model 4. It is based on the SAM of De Lucia & Blaizot (2007), transformed to the language of Neistein & Weinmann (2010) and including the following modifications:

- SF efficiency (the ratio between the SFR and the cold gas mass within the disk) is lower in small mass haloes.
- Satellite galaxies experience stripping of hot gas in proportion to the stripping of dark-matter, following the suggestion of Weinmann et al. (2010) (see also Khochfar & Ostriker 2008).
- Cooling is suppressed within haloes that are more massive than $5.6 \times 10^{11} h^{-1} \text{M}_\odot$, and there is no SF within haloes of mass $> 5 \times 10^{12} h^{-1} \text{M}_\odot$ at $z < 1.3$. These ingredients are aimed to mimic the feedback from AGNs, although they do not depend on the specific AGN hosted by each galaxy.

- The dynamical friction time is assumed to depend on the cosmic time and is shorter at higher redshift. This behaviour is obtained by using the Chandrasekhar formula with a multiplication factor of $5 \times (t/13.6)^{0.5}$, where t is the time in Gyr since the big-bang. This dependence is motivated by a more radial infall of satellite galaxies towards the centre of their group at high redshifts (Hopkins et al. 2010; Weinmann et al. 2011).

- The SFR in merger induced bursts depends on the halo mass. In particular, it is lower than the approximation used by De Lucia & Blaizot (2007) for haloes less massive than $3 \times 10^{11} h^{-1} M_\odot$. The specific implementation is described below.

Galaxies in our model are embedded within dark-matter subhaloes as extracted from the N -body simulation. We assume that the galaxies merge following the merging-time of their host subhaloes, with an additional time-delay. This delay is estimated using the Chandrasekhar formula for dynamical friction (see Wang et al. 2012). Mergers trigger SF bursts, with an efficiency that depends on the mass ratio of the two galaxies. The total stellar mass formed in the merger induced burst is:

$$\Delta m_{s,burst} = \begin{cases} 0.56 \left(\frac{m_2}{m_1} \right)^{0.7} m_{cold} & \text{if } M_h \geq M_0 \\ 0.56 \left(\frac{m_2}{m_1} \right)^{0.7} m_{cold} \frac{M_h}{M_0} & \text{otherwise} \end{cases} \quad (1)$$

where m_1, m_2 are the baryonic masses of the central and satellite galaxy respectively (including both stellar and cold gas mass), m_{cold} is the sum of the cold gas masses of the two galaxies, M_h is the mass of the descendant subhalo, and $M_0 = 3 \times 10^{11} h^{-1} M_\odot$. For high mass galaxies, this recipe follows the results of hydrodynamical simulations by Mihos & Hernquist (1994) and Cox et al. (2008), and was adopted by various SAMs (e.g. Somerville et al. 2001; Croton et al. 2006; Khochfar & Silk 2009; Neistein & Weinmann 2010; Khochfar et al. 2011). For low mass galaxies this recipe is motivated by recent observations of SF efficiency (Wang et al. 2012). Note that mergers provide the only trigger for SF bursts in our model. The other mode of SF, by secular processes, describes the relatively slow conversion of cold gas into stars within disk galaxies.

The specific model used here is able to fit the SF histories of galaxies to a higher accuracy than most other SAMs (see Henriques et al. 2012, for a recent success in this respect). As was shown in Neistein & Weinmann (2010), our models reproduce both the stellar mass function of galaxies up to $z = 4$, and the distribution of SFRs at $z = 0$. In Wang et al. (2012) we further improved the model to reproduce the auto-correlation function of galaxies at $z = 0$. These results are unique in comparison to other SAMs, allowing us to use reliable SF histories of galaxies as a basis for the work presented here which focuses on BH evolution. The model fits observations to a level of 20-40 per cent, and is probably not the only possible galaxy formation model. In particular, there is a degeneracy between the amount of stars formed in mergers induced bursts, versus the amount of star formation due to secular processes.

The duration of SF bursts has a negligible effect on the statistical properties of the model galaxies. This is because these events are rare, and hardly contribute to the total SFR density of the Universe. However, in our current study, bursts are the only channel of BH growth, and their duration plays an important role in the model. We assume that the shape of SF bursts follows a Gaussian as a function of time, with the following parameterization:

$$\frac{dm_{s,burst}}{dt} = \frac{\Delta m_{s,burst}}{\sigma_b \sqrt{2\pi}} \exp \left[-\frac{(t - t_0)^2}{2\sigma_b^2} \right]. \quad (2)$$

Here σ_b determines the burst duration, t is the time in Gyr since the big-bang, and t_0 is the time of the peak in the SF burst. We assume that t_0 occurs $2\sigma_b$ after the time the galaxies merge, to allow a smoothly rising peak of SFR (the burst of SF starts at the time of merging). We allow the burst to continue forming stars up to $4\sigma_b$ after t_0 , so the total duration of the burst is $6\sigma_b$.

At higher redshifts galaxies have smaller radii, and time-scales are shorter (the halo dynamical time is proportional to the cosmic time, t). We therefore assume that σ_b depends on t in the following way:

$$\sigma_b = \sigma_0 \frac{t}{13.6} \text{ Gyr}, \quad (3)$$

where σ_0 is a free constant.

An additional important ingredient of the model is the definition of the bulge mass. We assume that galaxies can grow a bulge according to two different channels. First, SF bursts that are triggered by mergers of any mass ratio are assumed to contribute their stellar content to the bulge (i.e., $\Delta m_{s,burst}$ from Eq. 1 is added to the bulge of the remnant galaxy). Second, once the mass ratio m_2/m_1 is larger than 0.3, the *total* stellar mass of both galaxies is moved to the bulge of the remnant galaxy. Therefore, the mass of stars within the bulge might be larger than the total amount of stars formed within bursts.

2.2 Black holes

Our SAM assumes that BHs grow only during merger induced star bursts. The masses of seed BHs in this model are extremely small in comparison to the mass added in the first merger event and make no difference to the accumulated mass of BHs at relatively low redshifts. We have tested that using BH seeds of mass $10^3 M_\odot$ does not change our model results significantly.

When galaxies merge, we merge their corresponding BHs at the same time. Following each merger event, a burst of SF occurs according to Eqs. 1-3. We allow the remnant BH to grow in mass according to:

$$\frac{dm_{BH}}{dt} = \begin{cases} (1 - \eta) \frac{dm_{s,burst}}{dt} \alpha_{acc} & \text{with probability } \alpha_p \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

Here η is the fraction of mass that is transformed into radiation and α_{acc} is a free parameter, corresponding to the efficiency of BH accretion with respect to the SF burst.

In a Λ CDM universe, the fraction of galaxies with an active SF burst at any given time is high, especially due to the non-negligible burst duration σ_b . However, observations show that the number of AGNs is significantly lower (e.g. Croom et al. 2009). Our model assumes that only a fraction α_p of the merger events induce accretion into the BH. In practice, at each time-step of the SAM (with a typical duration of 10 Myr) and for each BH we generate a random number, distributed uniformly between zero and unity. We then allow accretion only if this random number is smaller than α_p . In practice, each merger event adds on average a mass of $\alpha_{acc} \alpha_p \Delta m_{s,burst}$ to the BH.

The bolometric luminosity of the AGN is defined as:

$$L_{AGN} = \frac{\eta}{1 - \eta} \frac{\Delta m_{BH}}{\Delta t} c^2, \quad (5)$$

where Δt is the length of the time-step within the SAM (~ 10 Myr), Δm_{BH} is the total mass that is added to the BH within a time-step (i.e., the integration of Eq. 4), and c is the speed of light.

The Eddington luminosity describes the limit at which radiation pressure balances the gravitational force of the BH

$$L_{\text{Edd}} = 1.5 \left(\frac{m_{\text{BH}}}{10^8 M_{\odot}} \right) 10^{46} \text{ erg s}^{-1}, \quad (6)$$

where the factor 1.5 on the left is derived for solar metallicity gas. In our model, the accretion into the BH is determined by the SF burst, and might be above the Eddington limit. In addition, it is reasonable to assume that this limit will vary between different BHs. In order to use a practical accretion limit, we define λ_{Edd} to be a log-normal random variable (i.e. its log value is normally distributed) with a mean of $\lambda_{\text{Edd},0}$ and a standard deviation of σ_{Edd} (in log). For each accretion event, we randomly choose a value for λ_{Edd} and do not allow L_{AGN} to exceed $L_{\text{Edd}} \lambda_{\text{Edd}}$. We will refer to $L_{\text{Edd}} \lambda_{\text{Edd}}$ as the Eddington *threshold*, since it is being used to actively limit the accretion onto BHs. We note that we do not use the Eddington threshold for the first accretion event (i.e. when the BH mass equals zero).

At low accretion rates we use the properties of ‘advection dominated accretion flows’ (ADAFs). As in previous studies (e.g. Fanidakis et al. 2012) we model the ADAF limit by

$$\eta_{\text{ADAF}} = \frac{L_{\text{AGN}}}{L_{\text{Edd}}} \frac{\eta}{\alpha_{\text{ADAF}}} \quad (7)$$

which is valid only for $L_{\text{AGN}}/L_{\text{Edd}} < \alpha_{\text{ADAF}}$. By definition, η_{ADAF} equals η when $L_{\text{AGN}}/L_{\text{Edd}} = \alpha_{\text{ADAF}}$. In this work we fix α_{ADAF} to a value of 0.01.

Some of the results presented here make use of the luminosity of AGNs in the *B* band. For the conversion between L_{AGN} and *B* band we use the bolometric correction from Marconi et al. (2004):

$$\log(\nu_B L_{\nu_B} / L_{\text{AGN}}) = -0.8 + 0.067 L_1 - 0.017 L_1^2 + 0.0023 L_1^3, \quad (8)$$

where $L_1 = \log(L_{\text{AGN}}/L_{\odot}) - 12$. The absolute magnitude in the AB system is then given by

$$M_B = -11.32 - 2.5 \log(\nu_B L_{\nu_B} / 10^{40} \text{ erg s}^{-1}), \quad (9)$$

where *B* refers to a rest wavelength of 4400 Å.

To summarize, our SAM includes all the ingredients from Wang et al. (2012) related to galaxies, with the following additional parameters related to the evolution of BHs: η , α_{acc} , α_p , $\lambda_{\text{Edd},0}$, and σ_{Edd} . These parameters are presented in Table 1 and their best chosen values are justified in section 3. The ingredients used here are similar to previous SAMs (e.g. Malbon et al. 2007), although we do not include growth modes that are not due to bursts (e.g. Hirschmann et al. 2012).

Finally, we note that the model is limited both in terms of the minimum BH mass that is properly resolved, and in terms of the limited volume of our simulation box. These limitations originate from the limited dynamical range of the Millennium simulation that is being used here, and will be discussed below.

3 RESULTS

3.1 Observational constraints and best model parameters

In this work we treat the galaxies as priors and do not change the parameters that affect their evolution, except for the value of σ_0 , which has a negligible effect on the properties of galaxies. Consequently, there are only six free parameters in the model, as listed in Table 1. However, the low density of AGNs in the Universe forces us to test each set of model parameters by using the full Millennium simulation, spending a few CPU hours on each run. In order

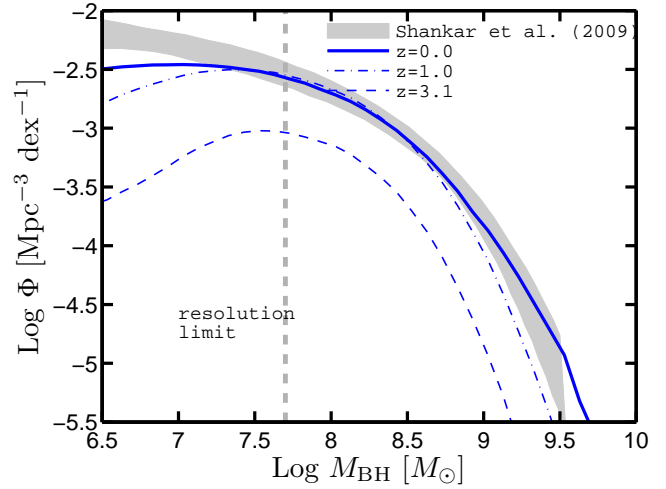


Figure 1. The mass function of BHs. The shaded region represents the observational prediction from Shankar et al. (2009) based on the correlation between bulge and BH masses at low redshift. Different line types correspond to the model mass function at various redshifts as indicated. The grey dashed line shows the minimum BH mass that is reliably reproduced by the model (due to a minimum subhalo mass of $1.72 \times 10^{10} h^{-1} M_{\odot}$).

to achieve fast tuning, while still running our model on the full simulation box, we first save all the model results that are related to the evolution of galaxies. We then run the BH ingredients only, thus saving a large amount of computational time. Our tuning procedure can evolve BHs over the full Millennium simulation in only three minutes (using one processor), allowing us to systematically explore a large region of the parameter space.

We use three different types of observations to constrain our model parameters: the luminosity functions of AGNs at $0 < z < 4$, the mass function of BHs at $z = 0$, and the relation between SFRs and AGN luminosities. While we further compare the model to other observations in the following sections, these additional observations were not used for tuning the model.

3.1.1 The mass function of BHs and the luminosity functions of AGNs

We start by tuning the model parameters against two common observations: the mass function of BHs at redshift zero, and the luminosity function of AGNs at $z < 4$. We apply a tuning procedure that systematically scans a range of the parameters α_{acc} , α_p , $\lambda_{\text{Edd},0}$, σ_{Edd} according to the range listed in Table 1. The value of σ_0 can significantly affect the luminosity function of AGNs. However, it is fixed here due to its effect on the relation between SFRs and AGN luminosities, that will be discussed in the next section. Using the prior value of $\sigma_0 = 0.13$ Gyr, we could not find a model that matches the data to a satisfying accuracy, while using constant values for all the parameters. We note that larger values of σ_0 allow for better models. Consequently, we choose to add a dependence on time for α_{acc} . It should be noted that a similar result as shown here could arise from varying the parameter α_p with time. We will discuss below the degeneracy in choosing the best solution, and its relation with the SFR values of our model galaxies. Our best model uses $\eta = 0.05$, consistent with a value of 0.057 obtained for non-rotating BHs.

In Fig. 1 we show that the mass function of BHs from the

Table 1. The free parameters used to model BHs and AGNs.

Parameter	range	best value	description
σ_0	0.1-0.5 Gyr	0.13 Gyr	Burst duration, Eq. 3
η	0.05-0.3	0.05	Radiative efficiency, Eq. 4
α_{acc}	0.001-0.3	$0.185(t_1^2 - 1.68t_1 + 0.75)$	Accretion efficiency, Eq. 4, $t_1 = t/13.6$ Gyr
α_p	0.001-0.1	0.04	Fraction of mergers that result in AGN activity, Eq. 4
$\lambda_{Edd,0}$	0.1-3	1.0	Eddington threshold (mean)
σ_{Edd}	0-1	0.7	Eddington threshold (scatter)

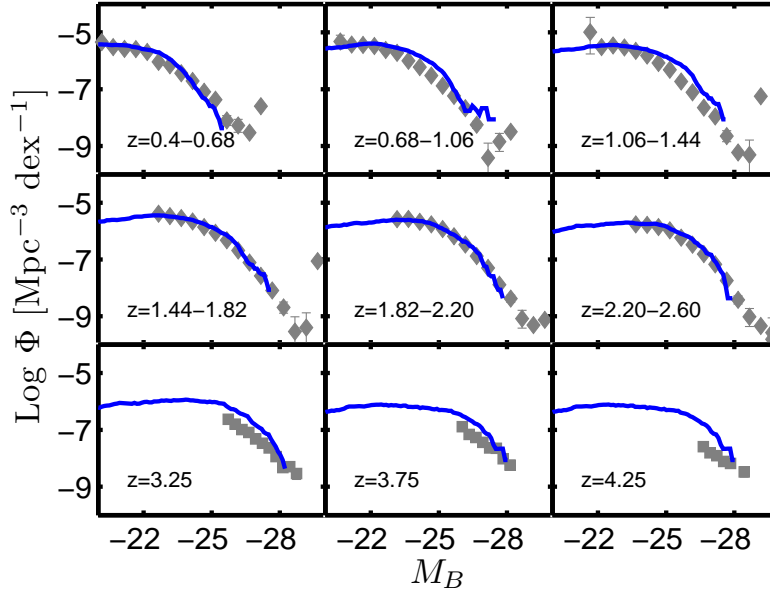


Figure 2. The luminosity functions of AGNs. Each panel shows one redshift bin as indicated. Observational results from Croom et al. (2009) and Richards et al. (2006) are plotted in *diamonds* and *squares* symbols respectively. Following Eq. 2 and 3 from Croom et al. (2009), we add 0.587 and 0.817 magnitudes to M_g and M_i respectively, in order to convert them to M_B (note that in these papers M_g and M_i are defined for rest wavelengths corresponding to $z = 2$ and hence require correction factors to compare with our computed B band at a wavelength of 4400Å). Model results are plotted in *solid* lines.

model at $z = 0$ agrees with the prediction from Shankar et al. (2009). The results from Shankar et al. (2009) are based on the mass function of galaxies, combined with the correlation between the bulge and the BH mass. It is therefore not a direct observation, and should not be considered as a strong constraint. However, the mass function points to important features of the model and we choose to use it as a constraint even though the actual values are not certain. For example, the recent work by McConnell & Ma (2012) indicates that the ratio between the mass of bulges and BHs could reach a level of ~ 100 at the high-mass end. Fig. 1 also shows the model mass functions at higher redshifts, indicating that the number of low mass BHs grows fast before $z \sim 1$ and changes only slightly at $z < 1$.

As seen in Fig. 1, the computed mass function declines at $\log m_{BH}/M_\odot \lesssim 7.7$. We have tested a lower resolution model by allowing BHs to grow only within subhaloes more massive than $10^{11} h^{-1} M_\odot$. This mimics a low-resolution simulation with respect to the actual minimum mass of the simulation ($1.72 \times 10^{10} h^{-1} M_\odot$). Within this resolution test, the bend in the mass function occurs at a larger mass, indicating that our resolution limit is indeed the reason for the bend at $\log m_{BH}/M_\odot \lesssim 7.7$. Our lim-

ited resolution has a negligible effect on other results shown in this work.

Models based on high resolution merger trees could possibly solve the above resolution problem (e.g. Fanidakis et al. 2012). Since it is difficult to increase the mass resolution within cosmological simulations, this issue could be addressed by using Monte-Carlo algorithms for generating merger-trees of haloes (e.g. Somerville & Kolatt 1999; Parkinson et al. 2008; Neistein & Dekel 2008). However, the merger-trees used here are based on subhaloes, and are more accurate than the theoretical merger trees based on haloes. We plan to check the use of Monte-Carlo merger trees in a future study.

The luminosity functions (LFs) of AGNs are shown in Fig. 2 where points are observations adopted from Croom et al. (2009), Richards et al. (2006) and solid lines are the model results. The theoretical LFs computed by the SAM are in broad agreement with the observations. In case we use constant α_{acc} the LFs at $z < 1$ are higher than the observed ones.

It should be noted that our simulation volume is smaller than the observed volume at $z \gtrsim 2$, giving rise to some of the deviations seen at high luminosities at this redshift range. Furthermore, we do not take into account various effects that could change the model at

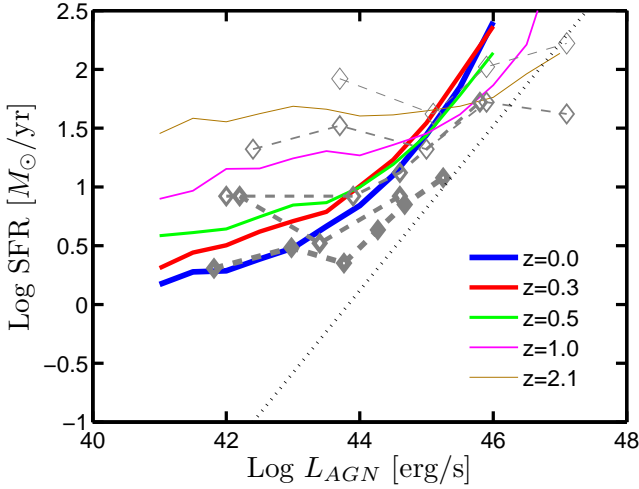


Figure 3. The average SFR for host galaxies of a given AGN luminosity. Observational results from Rosario et al. (2012) are shown in grey dashed lines, where thinner lines correspond to higher redshifts. The observed error bars are typically at the level of ± 0.2 and ± 0.5 dex, for SFR and L_{AGN} respectively. Model results using the same averaging scheme and the same redshift bins are plotted in solid lines with redshifts as indicated. For reference, we plot in dotted line the relation $\text{SFR} \propto L_{\text{AGN}}^{0.7}$ (the plot is referred to in the paper as the ‘rates diagram’).

the level of ~ 30 per cent. For example, it is well known that some AGNs are obscured and would not be accounted for in the observed LF. We have tested that using the slim-disk approximation for super Eddington accretion rates (e.g. Fanidakis et al. 2012) does not change the model results. Lastly, re-tuning the ingredients related to galaxy-formation might further improve the model results. We neglect all these effects in order to keep our model as simple as possible.

Most of the free parameters in our model have a simple effect on the LF. Since the SF bursts of galaxies are not modified, α_{acc} behaves as a constant multiplication factor for the luminosity of all AGNs at a given redshift. Changing α_{acc} thus induces a lateral shift in the luminosity function. The value of α_p changes the number of bursts leading to BH activity, and therefore shifts the luminosity function along the Y-axis. Both α_{acc} and α_p are degenerated at some level, yielding similar results for different combinations with the same value of $\alpha_{\text{acc}}\alpha_p$. The value of η is similar in its effect to α_{acc} . In addition, it changes the relations between mass growth (i.e. the mass function of BHs) and luminosity. The parameters of the Eddington threshold, $\lambda_{\text{Edd},0}$ and σ_{Edd} , change mostly the high-end part of the luminosity functions, and also the mass function of BHs. These two parameters do not have a simple effect on the model results. When neglecting the Eddington threshold, the luminosity of AGNs only depends on the SFR within bursts, and not on the BH mass. In this simplified case, the LF of AGNs has the same shape as the number-density of SFRs in the model.

3.1.2 Star-formation rate and AGN luminosity

In Fig. 3 we show the observed results from Rosario et al. (2012) in grey dashed lines. Values along the X-axis correspond to the bolometric luminosity of X-ray selected AGNs. The original Y-axis of this plot corresponds to the rest-frame luminosity at a wavelength of $60\ \mu\text{m}$, stacking all galaxies that host AGNs with similar L_{AGN} .

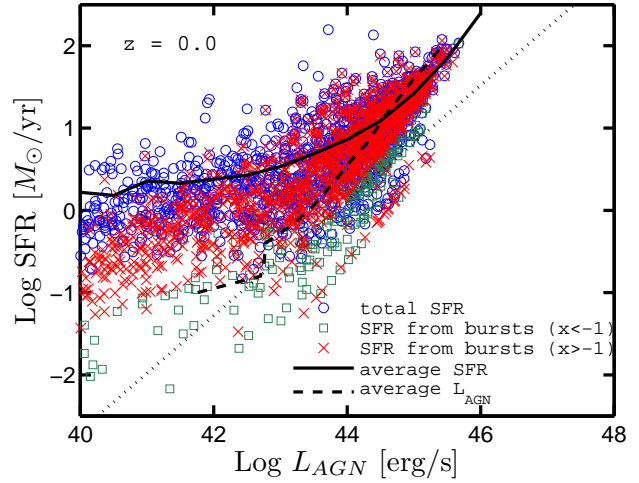


Figure 4. The rates diagram: values of SFR versus L_{AGN} at $z = 0$. Circles represent the SFRs and AGN luminosities of the model galaxies. Cross and square symbols show the level of SFR for the same objects, when considering contributions from SF bursts only (symbols are plotted for 20 per cent of the objects). We use the variable $x = (t - t_0)/\sigma_b$, where $x < -1$ corresponds to objects in the early stages of the burst. The thick solid line shows the average SFR value for a given L_{AGN} , as was computed in Fig. 3 (i.e., based on the total SFRs). The dashed line corresponds to the average value of L_{AGN} , for a given value of total SFR.

In order to transform the IR luminosity into SFR, we use the relation $L_{\text{IR}} = 3.8 \times 10^{43} \text{ SFR (erg s}^{-1}\text{)}$ and $L_{60\mu\text{m}} = 0.5 L_{\text{IR}}$, where SFRs are given in units of $\text{M}_{\odot} \text{ yr}^{-1}$. The corresponding SFR values are thus population averages for various redshift groups and do not represent individual objects.

Interestingly, as discussed in Rosario et al. (2012), for $z \geq 1$ there is hardly a correlation between the AGN luminosities and SFRs. At $z < 1$ the correlation between SFRs and AGN luminosities only exist for $L_{\text{AGN}} > 10^{44} \text{ erg s}^{-1}$. These findings seem surprising, since we expect that AGN growth modes will be coupled to the properties of their host galaxies. A lack of correlation might indicate that most AGNs are triggered by processes that are not related to the dominant mode of SF. In addition, it does not seem obvious that the correlation for bright AGNs only exist at low redshifts. In what follows, we term this plot as the ‘rates diagram’, since it shows the relation between BH accretion rates, and SF rates of their host galaxies.

An explanation for the rates diagram should take into account the various time-scales that are buried within this relation. First, the observations of SFRs are based on indicators that last ~ 150 Myr (this is a combination of both UV light emission from young stars, and dust heating that yields IR luminosity). Hence the observed SFR values reflect some of the recent history of the galaxy. To follow the same effect in the model, we compute the average SFR for each galaxy over time, taking into account the last 150 Myr before the output snapshot. Second, AGN luminosities represent an instantaneous emission, assumed by the model to last for ~ 10 Myr. Third, the duration of both the burst of SF and AGN activity is $6\sigma_b \approx 0.06t$ (see Eqs. 2 & 3).

As a result of the SF time-scale, the observed value of the IR luminosity is affected by the secular SF that occurred before the burst. This luminosity is uncorrelated with the merger event and with the AGN luminosity. High luminosity AGNs are those that are observed at a time that is close to the peak of their accretion

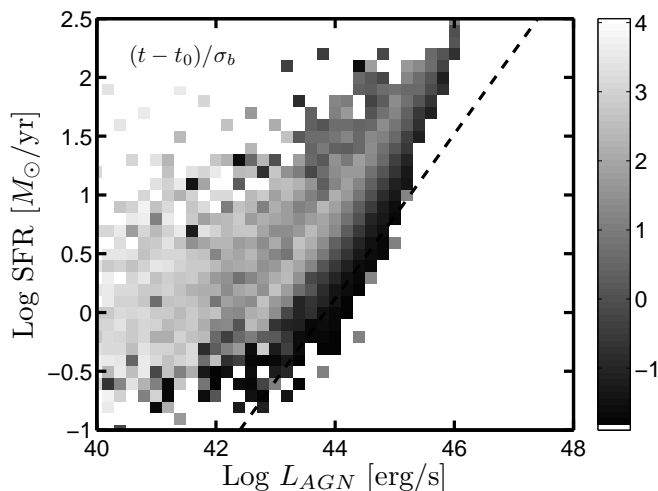


Figure 5. The temporal location of AGNs with respect to the peak luminosity of the burst. For each value of SFR and L_{AGN} we plot the median value of $x = (t - t_0)/\sigma_b$ (see Eq. 2). All AGNs are selected at redshift zero. The dashed line follows the relation $\text{SFR} \propto L_{\text{AGN}}^{0.7}$. AGNs that are starting their accretion episode lie on the right part of the diagram.

event (t_0 from Eq. 2). In these cases the SF burst is significant, and consists of most of the observed SFR value. This explains why the correlation between SFRs and AGN luminosities is only seen at high AGN luminosities. At $z = 2$, the secular SFR for star-forming galaxies is high, reaching the same level of SFR due to bursts in the most luminous AGNs. This is the reason for the lack of correlation between SFR and AGN luminosity at these redshifts.

At a given observed epoch t , different bursts have different values of t_0 and $\Delta m_{\text{s,burst}}$ only, as all other parameters do not vary between different objects. Since the time-scale for averaging the AGN luminosity is short, objects with the same value of $\Delta m_{\text{s,burst}}$ and $|t - t_0|$ will have the same values of L_{AGN} . However, these objects will have very different SFRs because those with $t > t_0$ will include the peak of SF within their SFRs, while for $t < t_0$ the SFR will mostly include the secular SF. This effect is more severe for larger values of $|t - t_0|$, and once the burst duration is smaller than the time-scale of SFR, contributing significantly to the scatter at low L_{AGN} .

In Fig. 4 we demonstrate these effects on our model galaxies at $z = 0$. We first plot individual SFRs and AGN luminosities from the model, and show how the average SFR is flat at $L_{\text{AGN}} < 10^{44}$ erg s $^{-1}$. We then plot for the same objects the SFRs that are calculated based on bursts only, taking out the contribution from the secular SF mode. The SFR due to the bursts is more correlated with the AGN luminosity. The remaining scatter between the bursty SFR and L_{AGN} originates from the fact that AGNs can be selected both before and after the peak (i.e. t_0 can occur before or after the observation). This changes the contribution to SFR from the burst itself, although the AGN luminosity is left unchanged. In Fig. 4 we show in different symbols AGNs that are selected before the peak of the burst, with $(t - t_0)/\sigma_b < -1$. For these objects, the correlation between SFR and AGN luminosity is strong, as expected. The strength of this last effect is smaller when σ_b is higher (even when using $\sigma_0 = 0.2$ instead of the current value of 0.13, the scatter due to different values of x becomes less dominant).

Our model suggests that only σ_0 and α_{acc} affect the rates diagram. Changing the value of σ_0 results in modifying the average

level of SFR for low L_{AGN} . On the other hand, α_{acc} shifts the diagram along the X-axis. Unlike the behaviour of the luminosity function, there is no simple degeneracy between these parameters here. The value of $\sigma_0 = 0.13$ Gyr that is chosen for the best model is obtained by matching the observed rates diagram.

We have tested how other standard SF modes affect the rates diagram and found that the L_{AGN} -SFR correlation is very sensitive to secular modes. For example, when using accretion into BHs that is proportional to the secular SFR, there are no regions with uncorrelated SFR and AGN luminosity. This is apparent even in cases where the BH growth in the secular mode is only 10^{-5} of the assumed SFR. As indicated by Fig. 4, the rates diagram originates from two effects. First, there is hardly a correlation between the SF within the burst and the secular SF. Second, the episodic nature of the burst together with the integration time of the SFR indicator. These two effects do not exist in a secular mode that is based on continuous BH accretion mode. However, different types of secular accretion, e.g. episodic events that were not tested by us, might show better agreement with the observed rates diagram.

The rates diagram as shown here is defined as the average SFR at a given AGN luminosity, and is not affected by the number of AGNs of different luminosities. However, once we compute the average AGN luminosity as a function of SFR (dashed line in Fig. 4), we see a different trend, in which SFR and L_{AGN} are always correlated. This way of averaging hides the flat part of the diagram, occupied by low luminosity AGNs, and is more dependent on the number of low-luminosity AGNs (i.e. on sample selection). Since the flat part of the rates diagram is highly restricting the models, the average L_{AGN} is less restrictive when comparing models to observations.

In Fig. 5 we plot for each value of SFR and AGN luminosity the median value of $x \equiv (t - t_0)/\sigma_b$. According to Eq. 2, x is the location within the Gaussian of the burst, where negative values (down to -2) correspond to the burst starting point, and positive values (up to 4) correspond to the late episode of the burst. Each burst starts on the left part of the rates diagram, with small AGN luminosity that is due to a value of $x = -2$. As x increases towards 0, both the SFR and L_{AGN} rise. Later on, when $x > 0$ L_{AGN} goes down to its initial level, while the SFR stays a bit higher, due to the integration over 150 Myr. As a result, the right part of the diagram is mostly populated with $x < -1$, and the higher values of L_{AGN} are related to $x \sim 0$. This effect modifies the correlation of $\text{SFR} \propto L_{\text{AGN}}^{0.7}$ (that is used by the model, Eq. 4) such that $\text{SFR} \propto L_{\text{AGN}}^{0.7}$, as observed by Netzer (2009).

3.2 Merger fraction

The main argument against a model of BH growth that is based only on mergers is the morphology of AGN hosts. As discussed in the Introduction, numerous works show that most AGNs reside in normal disk galaxies, with no sign of interaction. Here we test the observational constraint in this respect more closely.

In Fig. 6 we show the fraction of galaxies that host AGNs and are participating in major merger events, out of all galaxies that host AGNs. Major merger events are defined as those with mass ratio that is bigger than 0.3. Note that in the SAM, if a galaxy have more than one merger event, the mass ratio is determined by the event with the largest contribution to the SFR. A galaxy is considered to be a part of a merger event throughout the burst.

Fig. 6 shows that the results of the model are roughly consistent with those of Treister et al. (2012), although they deviate from the analysis of Kocevski et al. (2012). The model predicts that ma-

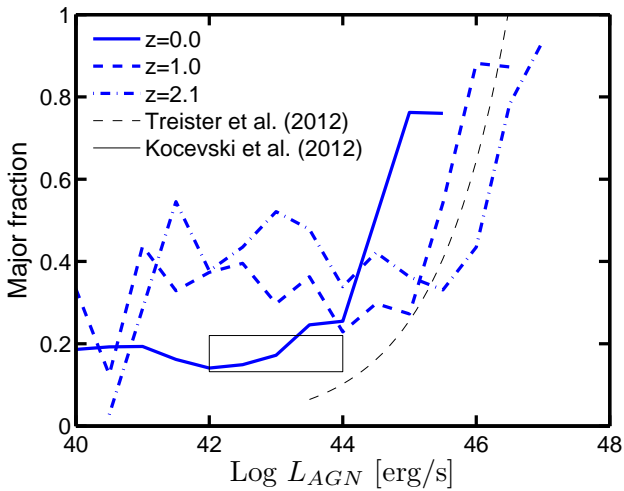


Figure 6. The fraction of galaxies that host AGNs and are going through major mergers (mass ratio is bigger than 0.3) out of all galaxies that host AGNs. *Thick* lines show the model results at various redshifts as indicated, after selecting all galaxies that host BHs with masses $\log m_{\text{BH}}/M_{\odot} > 7.7$. The *thin* dashed line shows the fitting function from Treister et al. (2012), obtained from a compilation of various studies at $0 < z < 1$. The grey boxy line shows the results from Kocevski et al. (2012), derived at $z \sim 2$.

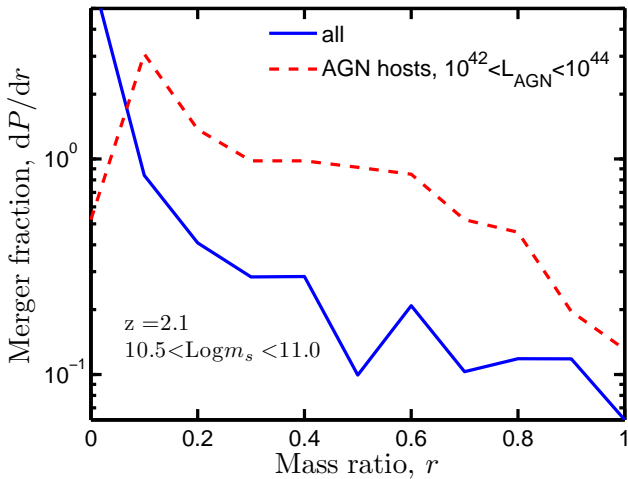


Figure 7. The fraction of galaxies undergoing a merger event with a mass ratio r . dP/dr is the probability distribution of galaxies of different r values. All galaxies are selected at $z = 2.1$ with stellar mass as indicated, in order to avoid resolution issues. The *solid* line corresponds to all the galaxies within the model. The *dashed* line shows the fraction out of all the galaxies that host an AGN with $10^{42} < L_{\text{AGN}} < 10^{44} \text{ erg s}^{-1}$, as were selected by Kocevski et al. (2012).

major mergers are associated with more luminous AGNs. There are a few limitations in this comparison that should be mentioned. First, we assume that the mass ratio for major mergers is 0.3, which is somewhat arbitrary. Second, we assume that the time-scale for detecting the morphological features within the galaxy is similar to the assumed duration of the burst. Third, we do not allow for a time-delay between the change in morphology and the onset of ac-

cretion into the BH. All these issues complicate the interpretation of the results.

A different way to examine this issue is to compare galaxies that host AGNs to a control sample of galaxies with the same stellar mass, that do not host AGNs. According to Kocevski et al. (2012), these two populations show similar fractions of galaxies that are detected as going through merger events. In Fig. 7 we make the same comparison with our model galaxies. This plot shows the fraction of galaxies going through a merger event of mass ratio r , after selecting only galaxies at $z = 2$, and with stellar mass $10.5 < \log(m_s/M_{\odot}) < 11$. The AGN sample includes galaxies hosting an AGN with $10^{42} < L_{\text{AGN}} < 10^{44} \text{ erg s}^{-1}$, similarly to the sample of Kocevski et al. (2012). This result shows that the fraction of galaxies going through a merger event is larger by a factor of ~ 2 for galaxies that host AGNs. Unlike the comparison made in Fig. 6, here the uncertainty is due to the existence of a time-delay between changes in morphology and the BH accretion phase.

3.3 Bulge and black hole mass

In Fig. 8 we show the relation between bulge and BH mass in our model. The ratio of the two masses depends on various factors. First, bulges can grow in major merger events by using the stellar mass from the disks of both progenitor galaxies. This effect will allow bulges to gain more mass than the total SFR during mergers, more than what is used for feeding the BH. In addition, the scatter between the bulge and BH masses should be a result of α_p , which allows for only a part of the burst events to feed the central BH.

Our model agrees with the results of both Häring & Rix (2004) and Sani et al. (2011) at redshift zero. However, the recent study by McConnell & Ma (2012) shows that at a bulge mass of $10^{12} M_{\odot}$ the BH mass is higher than what we get here, reaching $10^{10} M_{\odot}$. Our model BHs are less massive at the high mass end because we use the mass function from Shankar et al. (2009) for calibrating the mass of BHs in our model. In addition, the model predicts a smaller scatter in the mass relation for more massive objects in comparison to observations.

3.4 The distribution of BH masses for a given AGN luminosity

The distribution of BH masses, for a given value of L_{AGN} are shown in Fig. 9. The model predicts that most AGNs accretion is below the Eddington limit, especially at low redshift. At higher redshifts and high L_{AGN} the AGNs accretion is closer to the Eddington limit. The scatter we use for the Eddington threshold allow for some objects to slightly exceed the formal Eddington limit, mostly at high redshift.

3.5 Specific SFR in AGN hosts

Interestingly, our merger scenario naturally predicts that AGNs are hosted by massive star-forming galaxies. This can be seen in Fig. 10. Observations of this type were done by Salim et al. (2007) and Bongiorno et al. (2012) using different SFR indicators. This diagram is an extension of the rate diagram shown in Fig. 3, as it shows the full distribution of specific SFR, for each value of stellar mass. Results at higher redshifts are similar to what is shown here for $z = 0$.

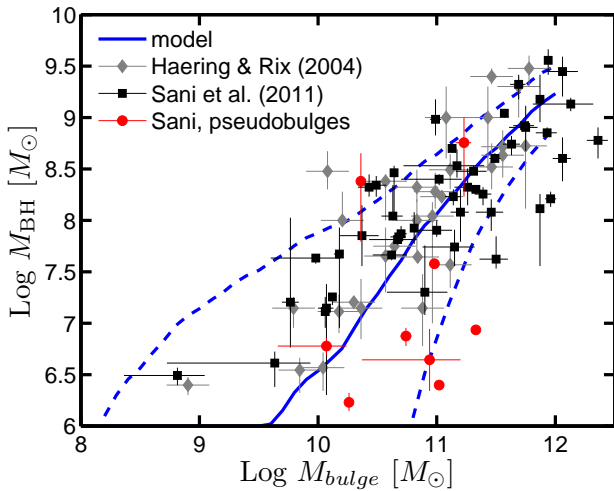


Figure 8. The relation between the masses of bulges and BHs at $z = 0$. Symbols correspond to the observational results from Häring & Rix (2004) and Sani et al. (2011). The thick solid line shows the median BH mass for a given bulge mass, taken from the model galaxies. Dashed lines show the 5 and 95 per cent levels of the BH distribution for each bulge mass.

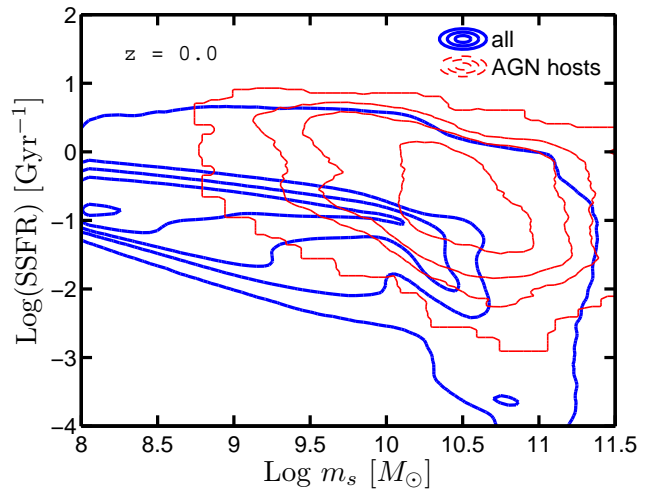


Figure 10. The distribution of specific SFR (SSFR) versus stellar mass at $z = 0$. Thick contours represent the distribution of all the model galaxies, while thin lines show the distribution of galaxies that host AGNs with $L_{\text{AGN}} > 10^{42} \text{ erg s}^{-1}$. Contour levels are at $\log P = -2.9, -1.4, -0.9, -0.4, 0.1$ where the integral of P equals unity.

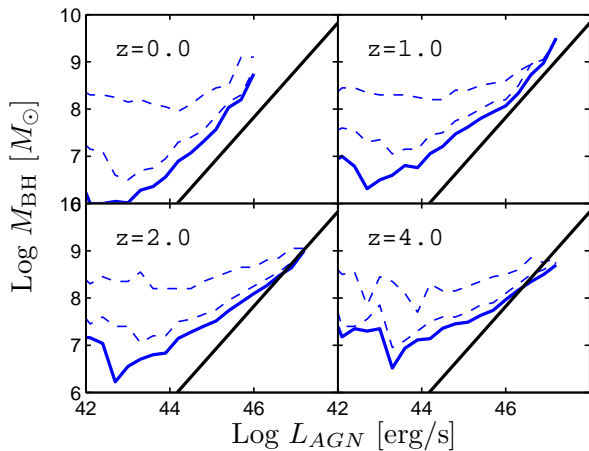


Figure 9. The distribution of BH masses as a function of AGN luminosities at various redshifts. The thick solid lines are the median values of the model. The dashed lines show the 67 and 95 per cent levels of the distribution. The thick straight line in each panel shows the Eddington luminosity, Eq. 6.

3.6 BH mass and accretion rate in the SFR- L_{AGN} plane

In Fig. 11 we show how other properties of AGNs depend on both SFRs and AGN luminosities at $z = 0$. We show that the model predicts a higher values of $L_{\text{AGN}}/L_{\text{Edd}}$ at higher L_{AGN} , with small dependence on SFRs. This is in spite of the lower values of $x = (t - t_0)/\sigma_b$ seen in Fig. 5 at high L_{AGN} and low SFRs. As a result, the Eddington ratio does not depend on x , the time within the burst. We have further tested that the Eddington threshold does not play a role at shaping the rates diagram at $z = 0$.

In the lower panel of Fig. 11 we show the median BH mass at each value of SFR and L_{AGN} . The scatter in masses around $L_{\text{AGN}} < 10^{44} \text{ erg s}^{-1}$ depends on the SFR but other regions of the diagram include more uniform distribution of BH masses.

4 SUMMARY AND CONCLUSIONS

This work presents a semi-analytic model (SAM) for the formation of galaxies and black holes (BHs) within a Λ CDM Universe. Our model is built on a galaxy-formation model that matches various observations of galaxies. These include the stellar mass function at $0 < z < 4$, the distribution of star-formation rates (SFRs) at $z = 0$, and the auto-correlation function of galaxies at $z = 0$. The results were developed in a previous study (Wang et al. 2012), and are adopted here with no further modifications to the properties of galaxies. When adding BHs to the model, we are interested in the properties of BHs and active galactic nuclei (AGNs), and how they correlate with the properties of their host galaxies. We do not take into account the possible feedback from AGNs on the physics of gas within galaxies.

Our model assumes that BHs grow only during star-formation bursts, with a probability α_p that is the same for all galaxies at all redshifts. The bursts in our model are only due to merger events; we do not model bursts from secular processes such as disk instability. When an event of BH accretion occurs, we assume that the gas mass that reaches the BH equals a fraction α_{acc} of the stars made in the burst at the same time. We use two additional parameters to describe the threshold on accretion due to the Eddington luminosity, in order to limit the accretion in case the burst is large and the BH mass is small. This model for the formation and evolution of BHs is therefore very simple, also in comparison to previous SAMs (Kauffmann & Haehnelt 2000; Croton et al. 2006; Bower et al. 2006; Malbon et al. 2007; Monaco et al. 2007; Somerville et al. 2008; Bonoli et al. 2009; Fanidakis et al. 2011; Fanidakis et al. 2012; Hirschmann et al. 2012).

The observational constraints used here are the mass function of BHs at redshift zero (Shankar et al. 2009), the luminosity function of AGNs at $z \lesssim 4$ (Richards et al. 2006; Croom et al. 2009), and the relation between SFRs and AGN luminosities (Shao et al. 2010; Rosario et al. 2012). We specifically study the latter constraint, as it was not tested by previous models. According to Rosario et al. (2012), AGNs at low redshift are related to a constant level of SFR within their host galaxies for $L_{\text{AGN}} < 10^{44} \text{ erg s}^{-1}$.

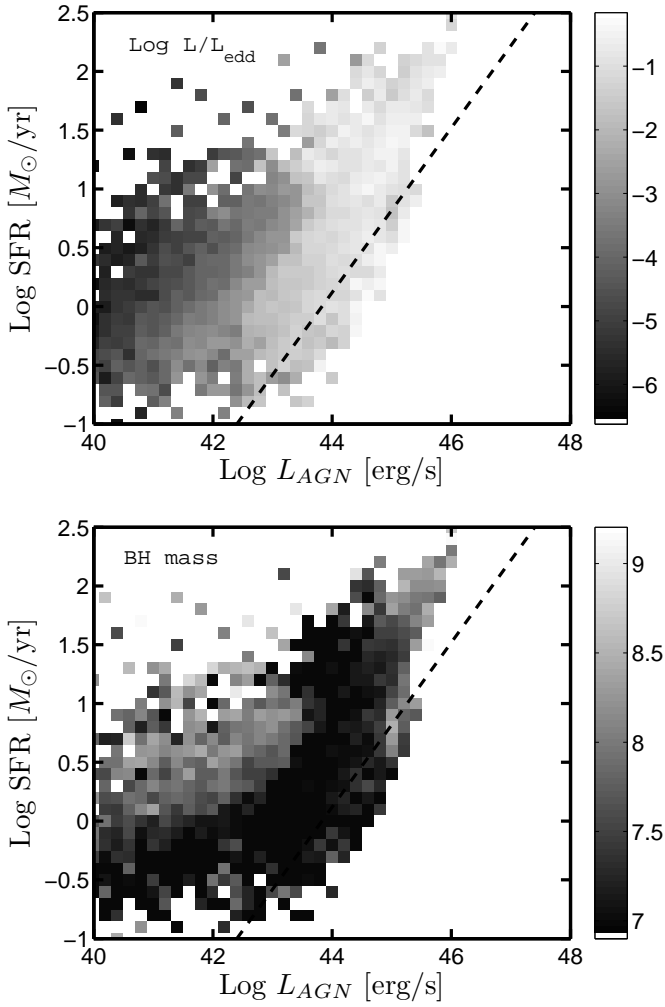


Figure 11. SFR versus L_{AGN} at $z = 0$. The *upper panel* shows the median Eddington ratio, $\log L_{\text{AGN}}/L_{\text{Edd}}$, at each bin. The *lower panel* represents the median BH mass in units of $\log M_{\odot}$. Here we set BH masses to a minimum value of $10^7 M_{\odot}$.

s^{-1} . At higher AGN luminosity, where L_{AGN} is larger than the luminosity of SFR, a power-law type correlation, $\text{SFR} \propto L_{\text{AGN}}^{0.7}$ is seen (see also Netzer 2009). At $z \sim 2$, AGNs of all luminosities are hosted within galaxies of the same average SFR, at a level of $\sim 30 M_{\odot} \text{ yr}^{-1}$. We term these results as the ‘rates diagram’, since it shows the relation between the star-formation rate, and the rate of BH growth.

As was demonstrated in Figs. 3 & 4, our model fits well the observed rates diagram. A necessary condition for the agreement is that we adopt the correct time scales for both SF and AGN activity. We therefore assume that the luminosity at $60\mu\text{m}$ used by Rosario et al. (2012) represent an averaging of 150 Myr over the SFR of each galaxy, and that the AGN luminosity is instantaneous (i.e. using the minimum time-step of our model, ~ 10 Myr). When using these time scales, we naturally reproduce the observed rates diagram. In our model, the lack of correlation between SFR and AGN luminosities is due to two main reasons: First, secular SF in galaxies are not associated with BH activity. Second, BH accretion before and after the peak in SFR could have the same AGN luminosity, but different SFR. A key assumption in the model is the lack of correlation between the properties of a galaxy prior to the merger

event, and the amount of star-formation within the burst, which depends on the properties of both merging galaxies. We thus argue that the rates diagram favours a mode of BH accretion that is due to mergers.

The rates diagram is used here for constraining the duration of the bursts in our model and for constraining the BH accretion factor, α_{acc} . The diagram is very sensitive to secular modes of BH growth (i.e. modes that do not depend on merger events). Even a small level of BH accretion from the secular mode, which adds a negligible mass to BHs, can modify the rates diagram considerably. Although we do not model such scenarios here, more constraints could be obtained by measuring the SFR in the central regions of galaxies (e.g. Stern & Laor 2012).

Visual classification of AGN hosts indicates that most AGNs are located within normal disk galaxies, with no signs of mergers (Gabor et al. 2009; Cisternas et al. 2011; Kocevski et al. 2012; Schawinski et al. 2012; Treister et al. 2012). We show in Figs. 6 & 7 that a similar result is obtained here, using a model with BH growth coming only from mergers. This is because most BH accretion is associated with minor merger events, which are difficult to detect observationally. However, our model shows that a typical galaxy has roughly half the chance to experience a merger event in comparison to a galaxy of the same stellar mass that hosts an AGN. We do not test in this work the possibility of having a time-delay between the merger event and the episode of BH accretion. Such a time-delay will further decrease the amount of AGN hosts that are showing morphological signs of interactions.

The model parameters used here were tuned to fit the observed mass function of BHs at $z = 0$, and the luminosity function of AGNs at $z \lesssim 4$. In addition, our final model agrees with the observed correlation between the mass of bulges and BHs (Häring & Rix 2004; Sani et al. 2011; McConnell & Ma 2012). We show in Fig. 10 that our model predicts that AGN hosts are relatively massive, and star-forming galaxies.

Finally, we provide predictions for the mass of BHs, and their Eddington ratios, within the rates diagram, as a function of both SFR and L_{AGN} . These predictions could be used to test the model against new observations.

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